Environment-induced pulmonary oedema in healthy individuals

Infrequently, healthy individuals can develop acute pulmonary oedema when exposed to an extreme or unusual environment (ie, deep dives or high altitudes), especially during physical exertion. High-altitude pulmonary oedema (HAPO) has been reported in 0·5–7·0% of individuals who climb to altitudes higher than 4000 m (according to ascent speed), whereas swimming-induced pulmonary oedema (SIPO) has been reported in a different proportion of individuals engaged in aquatic activities. The prevalence of SIPO ranges from sporadic cases in scuba divers, to 1·4% in swimming triathletes, and up to 25% in high-level and trained breath-hold divers. The pathophysiological mechanisms of these syndromes are not completely understood, but hypoxia, pulmonary capillary congestion (either induced by physical exercise or by increased venous return), and evidence of alveolar fluid rich in high-molecular-weight proteins seem to be common elements. Moreover, individuals prone to HAPO or SIPO share a high prevalence of genotypes associated with reduced activity of endothelial nitric oxide synthase. These observations could suggest that both HAPO and SIPO might be clinical manifestations of a unique disease that is primed by exposure to extreme (even if diametrically opposite) environments, and that breath-holding and immersion might be stronger triggers for pulmonary oedema than high-altitude climbing. Here, we explore the current evidence supporting these hypotheses.

Regarding the pathogenesis of HAPO, it seems that reduction of the partial pressure of oxygen in alveoli (PAO2) due to high altitude is a powerful stimulus for pulmonary arteriolar constriction. HAPO-prone individuals have exaggerated and uneven hypoxic pulmonary vasoconstriction, leading to an exaggerated rise in pulmonary arterial pressure that, particularly when associated with an increased cardiac output due to physical effort, might lead to pulmonary capillary stress failure and pulmonary oedema. Areas of the pulmonary capillary bed that are not protected against hypoxia-induced pulmonary arterial hypertension, due to heterogeneous vasoconstriction, are particularly susceptible to an increase in pressure.

The high prevalence of SIPO in breath-hold divers suggests that the combination of breath-holding, body immersion, and exposure to high environmental pressure is a very effective trigger for SIPO. In the final part of a maximum-duration breath-hold dive, severe hypoxia can develop, triggering intense hypoxic pulmonary vasoconstriction and hypertension. Hypoxia-mediated impairment of left ventricular contractility has also been described during maximal breath-holding. During head-out immersion, a blood shift (estimated as around 700 mL of blood) from the peripheral to intrathoracic venous and capillary bed has been observed. This blood shift might congest the pulmonary capillary bed and predispose individuals to capillary stress failure. Additionally, physical exertion while diving could enhance mechanical stress on the capillary wall by increasing pulmonary blood flow.

During diving, environmental pressure increases linearly with depth. In a hypothetical fast dive to 30 m depth, a diver moves from 1 to 4 atmospheres of air pressure absolute, quadrupling environmental pressure in some 10 s. Studies with a submersible echocardiograph suggested that chest compression exerted by environmental pressure might impair diastolic left ventricular filling, inducing the haemodynamic pattern observed in constrictive or restrictive heart diseases. Impairment of left ventricular filling could increase left atrial pressure and pulmonary arterial wedge pressure (PAWP), contributing to pulmonary capillary stress failure.

Therefore, three different, overlapping stimuli during freediving might lead to pulmonary capillary stress failure: body immersion (increasing venous return and inducing pulmonary capillary congestion), breath-holding (leading to hypoxic pulmonary arterial vasoconstriction), and high environmental pressure (inducing chest squeezing and, in turn, impairing left ventricular filling and increasing PAWP).

In other aquatic activities, an intrathoracic blood-shift might cooperate with other factors to induce SIPO. For example, in high-intensity surface swimming, physical exertion can induce pulmonary capillary congestion, whereas, during scuba diving, a negative inspiratory
Comment

We declare no competing interests.

1 Sweensson ER, Bartsch P. High-altitude pulmonary edema. Compr Physiol 2012; 2: 2753–73.

Figure: Schematic representation of the interplay of the basic stimuli for environmental-induced pulmonary oedema in healthy individuals

Pulmonary capillary congestion
(exercise or immersion)

Hypoxia (high altitude or apnoea)

Exercise alone
Exercise-induced alveolar haemorrhage (racehorses)

Exercise and hypoxia

Immersion and hypoxia
(and chest compression)

Breath-hold diving SIPO

Immersion alone
Scuba diving SIPO

Exercise and hypoxia
Exercise-triggered HAPO

Immersion and hypoxia
Triathletes SIPO

Hypoxia alone
‘Pure’ HAPO

Individuals who breath-hold dive are exposed to the effects of hypoxia, central blood-shift, and chest compression. HAPO=high-altitude pulmonary oedema. SIPO=swimming-induced pulmonary oedema.

pressure gradient (due to the increased density of compressed air at depth and the added resistance of breathing apparatus) or hypoxia (due to an erroneous composition of the breathing mixture during mixed gas dives) might facilitate pulmonary oedema.

Previous research\(^1^\-\(^5\)\) suggests that acute pulmonary oedema arises in genetically predisposed healthy individuals exposed to different environments and depends on the interplay of three elements that lead to pulmonary capillary stress failure and, in turn, pulmonary oedema (figure). These elements are hypoxia (either due to hypobarism or prolonged apnoea), pulmonary capillary congestion (either due to body immersion or strenuous physical exercise), and chest compression (due to elevated environmental pressure), which leads to left ventricular diastolic impairment.\(^1^3^\-\(^1^4\)\) These elements might act separately in different environments but are simultaneously present during breath-hold diving, which thus represents the perfect environmental stressor to induce pulmonary oedema in healthy individuals.

The existence of a common pathogenetic background could allow translation of the preventive and therapeutic strategies for HAPO (ie, progressive acclimatisation to triggering stimuli, avoidance of excessive exertion while diving, and use of drugs that increase the availability of nitric oxide)\(^1^5\) into the still unexplored field of SIPO prevention and treatment.

\*Claudio Marabotti, Danilo Cialoni, Alessandro Pingitore
National Research Council Institute of Clinical Physiology, Pisa, Italy (CM, AP); Unità Operativa Cardiovascolare, Unità di Terapia Intensiva Cardiologica, Ospedale della Bassa val di Cecina, Livorno 57023, Italy (CM); and Divers Alert Network Europe, Roseto degli Abruzzi, Italy (DC)
c.marabotti@gmail.com

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\(NoS\) = nitric oxide synthase; \(HAPO\) = high-altitude pulmonary oedema; \(SIPO\) = swimming-induced pulmonary oedema.